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Column Access of a Bubble Lattice: Column Translation and Lattice Translation

Abstract: The use of a regular array, or lattice, of magnetic bubbles for the storage of information requires two kinds of functions: the read-write functions involving the generation and discrimination of bubbles with different wall structures, and the access functions involving the insertion and removal of bubbles at selected locations in the lattice. In a column-accessed bubble lattice device, accessing is accomplished by first translating the lattice to position the desired column of bubbles in an input-output access channel and then translating this column along the channel to a detector area outside of the lattice while simultaneously introducing new bubbles from a generator area at the other end of the channel. An analysis of the influence of device design parameters on access rate indicates that the most important parameters are the column translation rate and lattice capacity. A device is described that was designed to study the translation of a lattice of bubbles and of a single column of bubbles within the lattice. Quasistatic operating margins and dynamic measurements of this test device indicate that the column-access configuration provides feasible means for the rapid access of bubbles from a lattice.

Introduction

The use of regular arrays of closely spaced bubbles for information storage has been described previously [1]. These "bubble lattice devices" make use of the strong magnetostatic repulsion between closely spaced bubbles to determine the positions and motion of the bubbles. The bubbles form a regular hexagonal lattice [2, 3] and hence the presence or absence of a bubble cannot be used to represent information. Instead, information is stored in the wall structure of the bubbles [4] and is sensed by means of the influence of the wall structure on the dynamic behavior of the bubbles.

The attractiveness of bubble lattice devices is due to their potentially high storage density. The storage density of bubble memories which code information as the presence or absence of bubbles is limited by two factors. The finite resolution of the lithographic fabrication processes places a lower limit on bubble size, and the aperiodic domain interactions necessitate a bit separation of at least four bubble diameters. The lithographic constraint is determined by the design of the bit cell structure. Table 1 compares the lithographic feature size and bubble diameters required for a storage density of 10^5 bits/mm^2 (6.5×10^7 bits/in.^{2}). This density is about 20 times higher than present "state-of-the-art" T-bar bubble memories [5].

Table 1 Bubble diameter and feature size required for a storage density of 10^5bits/mm^2.

Technology	*Bubble diameter* (μm)	*Feature size* (μm)
Conventional T-bar	0.63	0.32
Bubble lattice	1.7 μm	1.7 μm

The various functions required for a bubble lattice device can be divided into two groups: (1) the read/write functions concerned with generating bubbles having the desired wall states and discriminating between bubbles with different states, and (2) the manipulative functions involved in creating and maintaining the regular lattice and in inserting and removing information-carrying bubbles from this regular lattice. The use of in-plane fields to control the states of bubbles generated in ion-implanted garnet films has been described by Hsu [6]. The effect of the gyrotropic force [7, 8] which causes bubbles in states $S \neq 0$ to deflect at an angle with respect to the direction of the applied magnetic field gradient has been described by several authors [9, 10]. In the EuYIG films we have used, bubbles with $S = +1$, i.e., those containing no Bloch lines, move at an angle of approximately 30° to the direction of the magnetic field gradient. This effect provides a convenient way of discriminating between $S = 0$ and $S = 1$ bubbles.

The manipulative functions required depend upon the organization of the device. In this paper, we discuss only the column-accessed organization [1]. As shown in Fig. 1, the lattice area contains several equally spaced access channels. To access a selected group of bubbles located within the same column, the lattice is moved laterally until this group is in the nearest access channel. Then the bubbles in the access channel are translated along the channel to a detector located outside the lattice. As the bubbles leave the channel, they are replaced by new bubbles produced in a generator located at the other end of the access channel. This reading process destroys the stored information and, if the record is not to be changed, the new bubbles generated must contain the same information as those destroyed. If the record is to be erased, the destroyed bubbles must be replaced by bubbles containing new information or by "dummy" bubbles (i.e., those containing no information) to maintain the regularity of the lattice. The column-accessed bubble lattice organization resembles somewhat the major-minor loop configuration of conventional T-bar memories. The access channels function in the same way as the major loops in a T-bar memory and the rows of the lattice correspond to the minor loops. In a column-accessed bubble lattice device, however, lattice translation (corresponding to propagation along the minor loops) and column translation (corresponding to propagation along the major loop) occur at different times in the operating cycle and not simultaneously, as they do in T-bar devices.

To investigate the feasibility of column accessing a bubble lattice, the device shown in Fig. 2 was designed, fabricated, and tested. The design of this device evolved from that presented earlier by Rosier et al. [11], and incorporates three new features: (1) the use of isolation barriers between every four rows of bubbles in the lattice, (2) the use of both bubbles and stripe domains in the buffer regions, and (3) conductor lines which are used to translate a column of bubbles along an access channel. This device allowed us to test the manipulative functions required for column accessing: isolation of the storage lattice from the surrounding domains, initial creation of a regular lattice of bubbles, translation of the bubble lattice, and translation of bubbles along the access channel. In this paper we first discuss the influence of various design parameters on the performance of a column-accessed bubble lattice device. We next discuss the design of the device shown in Fig. 2 and its fabrication, and then present the test results obtained with this device.

Organization and design considerations

We will limit the design considerations to the situation in which there is only one lattice storage area on each chip.

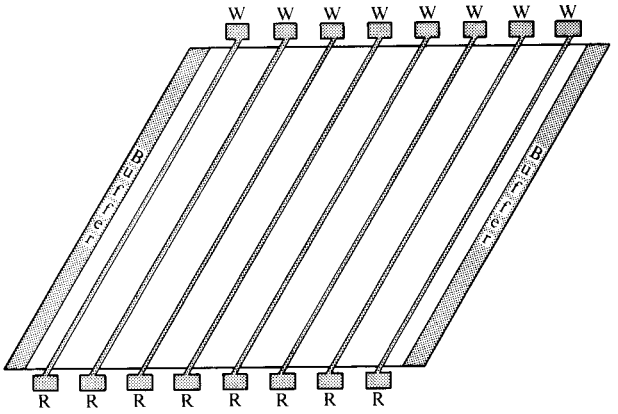

Figure 1 Organization of the column-accessed bubble lattice device.

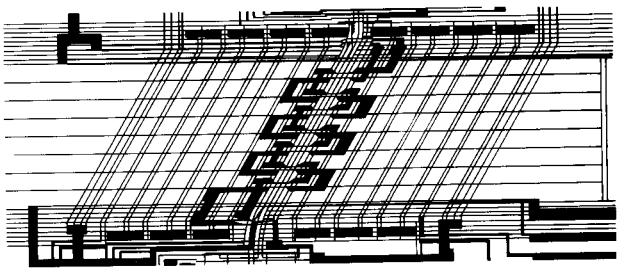

Figure 2 Experimental column-accessed device using raised barriers to provide isolation of bubbles within the lattice storage area from the domains in the surrounding area. Three superposed masks are shown.

The column-accessed organization of a bubble lattice device can then be described by five parameters: the number of access channels, n_a; the number of bubbles per column, n_b; the number of columns in the lattice, n_c; the time, T_c, required to translate the bubbles in the access channel a distance of one lattice; and the time, T_l, required to translate the lattice a distance of one lattice period. We are interested in how these parameters affect the areal utilization, i.e., the number of bubbles on a chip of a given size, and the performance of the chip. We use the access rate (the number of columns per second that can be translated to an access channel and propagated the length of the channel) to assess the chip design, since this is unaffected by other variables such as record length and the number of chips operated in parallel.

In addition to the area used for storage, space must be provided on the chip for generators, detectors, connecting pads, and buffer regions to allow lattice translation, which are a unique requirement of column-accessed bubble devices. The size of the buffer regions is n_a^{-1} times the lattice storage area. Although the quantitative

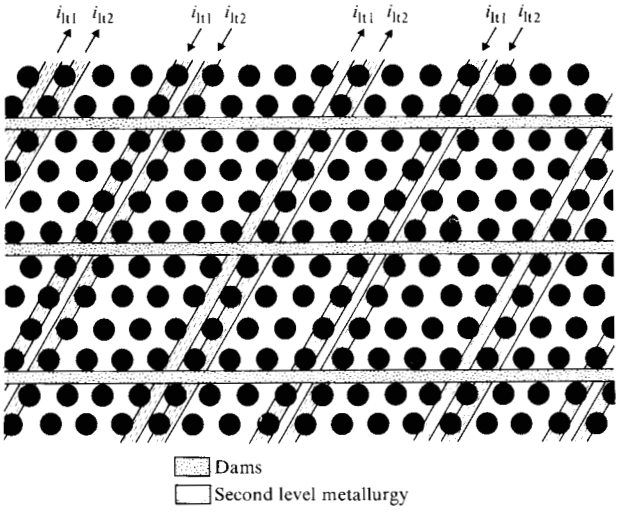

Figure 3 Diagram of a portion of the lattice, showing dams and lattice translation conductors. The series connections of these conductors outside the lattice area are indicated by arrows and the symbols i_{lt1} and i_{lt2}. For clarity, the portions of the lattice translation conductors that cross over the dams have been left out.

relations will be influenced by many details of a particular design, it is clear that the area required for generators, detectors, and pads will increase with the number of access channels. Therefore, there is an optimum choice of n_a which will minimize the total area required for nonstorage functions. In most cases, the optimum number of access channels will be between four and sixteen. For design purposes, we select $n_a = 8$.

The shape of the lattice storage area, a parallelogram with 60° angles, is determined by the symmetry of the bubble lattice. The requirement, imposed by the fabrication process, of fitting the chip design into a circular or square field dictates an aspect ratio n_c/n_b close to unity.

The access rate is the reciprocal of the time required to read a column of bubbles. This is the sum of the time intervals needed to position the column in an access channel and the time needed to translate the last bubble the length of the column. This neglects the small number of steps required to move a bubble from the edge of the lattice to the detector. The second time interval is a fixed quantity, equal to $n_b T_c$, but the first interval depends on the initial position of the lattice and the position of the selected column. The maximum number of lattice translation steps is n_c/n_a and, if the initial and final column positions are chosen randomly, it can be shown that the average number of lattice translation steps is one-third of this maximum. Thus, the access rate, A, is given by

$$A = \left(n_b T_c + \frac{n_c T_l}{3n_a}\right)^{-1} = \frac{1}{T_c}\left(\frac{R}{C}\right)^{\frac{1}{2}}\left(1 + \frac{R\tau}{3n_a}\right)^{-1}, \quad (1)$$

where $\tau = T_l/T_c$, the aspect ratio of the lattice $R = n_c/n_b$ and the storage capacity $C = n_b n_c$. As noted before, R will be close to unity and, therefore, for optimum performance, we want $\tau/3n_a \ll 1$. If $n_a = 8$, then a value of τ of two to five will not have a significant deleterious effect on the access rate. Decreasing the capacity, i.e., the size, of the lattice increases the access rate but this is unattractive because of the increase in the cost per bit of storage.

Experimental device

The experimental device, shown in Fig. 2, utilizes dam-like (raised) barriers formed by selective ion milling of the bubble material to provide isolation of the bubbles within the lattice storage area from the domains in the surrounding area. A new feature of this device is the provision of a dam between every four rows of bubbles in the lattice. These dams serve three main functions. First, the spacing between dams defines, to first order, the spacing between bubbles in the lattice. This, in turn, provides a means for matching the lattice parameter to the periodicity of the conductor lines used for lattice translation. The second function served by the dams is to stabilize the lattice in the direction orthogonal to the lattice translation. Both the gyrotropic force on $S = 1$ bubbles and the orientation of the conductors used to translate the lattice produce forces that tend to move the bubbles in the orthogonal direction. These forces are balanced by distortions of the lattice which are limited by the presence of the dams. The third, and perhaps most important, feature provided by the dams is associated with the column translation function. The conductor lines used for column translation produce a force on the bubbles in the lattice adjacent to the column being translated. The dams provide the structure that balances these forces and maintains the bubbles in the hexagonal lattice configuration. The choice of the number of rows of bubbles per dam involves a tradeoff between lithographic requirements and the maximum allowable variation in stripe width of the bubble material. For example, if we assume a bubble material with an equilibrium stripe width of 5 μm, then a design with one row of bubbles per dam would require a dam width of approximately 2 μm, with rather relaxed requirements on stripe width control. On the other hand, a design with ten rows of bubbles per dam would allow a dam width of perhaps 6 μm; however, the requirement of maintaining ten, and only ten, rows of bubbles per dam would limit the maximum variation in stripe width to less than ±5 percent. These considerations have led to the choice of four rows of bubbles per dam. The center-to-center spacing be-

tween dams has been chosen so as to produce a spacing between stripe domains which is equal to that of the equilibrium spacing between parallel stripe domains in a demagnetized state. This results in a lattice with a lattice period a_0 equal to $4w_s/\sqrt{3}$, where w_s is the demagnetized stripe width. The nominal value of w_s used in this device is 5.0 μm; therefore, the lattice period a_0 is 11.5 μm.

The design of the lattice translation conductors shown in Fig. 3 is similar to that used earlier [11] and is based on an analysis [12] that assumes that the lattice distortions during translation are negligibly small. The unequal spacing between pairs of conductor lines is due to the fact that the conductors are interconnected in series. The choice of the number of columns of bubbles per pair of conductor lines involves a tradeoff between power dissipation, lattice translation rate, and alignment requirements between mask levels. The series interconnection of conductor lines requires that a via hole mask be registered to the lattice translation conductor lines, and a second mask which is used to define the conductor interconnection metallurgy must then be registered to the via holes. The use of a small number of lattice translation conductor lines results in relaxed mask registration requirements at the expense of high power dissipation and low lattice translation rate. Conversely, a large number of lattice translation conductor lines implies low power dissipation and high lattice translation rate but tight mask registration requirements. As a compromise we have chosen a design with one pair of conductor lines per four columns of bubbles.

The lattice translation design previously described by Rosier et al. [11] utilized a buffer region of parallel stripe domains which expand and contract as the lattice is translated. The operating margins for that design showed a rather limited range in current. The failure mode at high current drives is associated with the stripe-bubble interface as this interface moves past a current-carrying conductor. To avoid this failure mode, we have chosen to use a buffer region design which has bubbles and stripe domains. As the lattice is translated, a column of bubbles is generated on one side of the lattice and a column of bubbles is annihilated on the other side of the lattice. The stripe domains serve as seed domains for the column generation process.

The geometry of the conductor lines used for column generation is identical to that used for lattice translation. As the lattice is translated a distance of one lattice period, the tips of the stripe domains move under the pair of column generation conductors, and opposing current pulses are applied to the two conductors to cut the tips of the stripe domains and thus form a column of bubbles. This process is repeated each time the lattice is translated a distance of one lattice period.

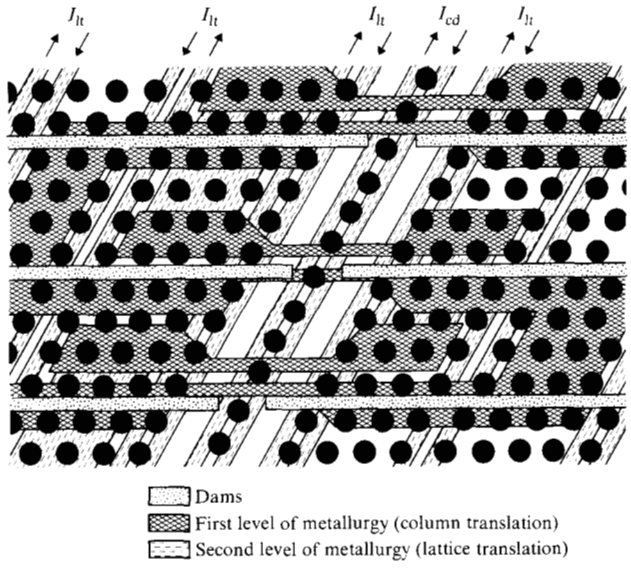

Figure 4 Design of conductors used for column translation, which are cross-hatched, and the openings in the dams. The conductors are on the first layer of metallurgy, interconnected in series by crossovers using the second layer. A pair of conductors provides a channel for the column of bubbles during translation. Current directions in the column definition conductors, i_{cd}, and in the lattice translation conductors, i_{lt}, are indicated by arrows. The parts of the conductors that lie on top of the dams or the first level of metallurgy have been left out.

The column annihilation process consists of translating the lattice a sufficient distance, using the lattice translation conductors, to position the column of bubbles to be annihilated between two column annihilation conductor lines. Opposing current pulses are then applied to the column annihilation conductors in such a direction as to increase the bias field between the conductor lines and thus annihilate the column of bubbles. After column annihilation, the current in the conductor holding the tips of the stripe domains is reduced to zero while the current in the conductor holding the column of bubbles adjacent to the stripe domains is maintained. This causes the tips of the stripe domains to extend into the region which was previously occupied by a column of bubbles. After the tips of the stripe domains have reached an equilibrium position, the current in the conductor holding the column of bubbles is reduced to zero. This process is repeated each time the lattice is translated a distance of one column position. Thus, each time the lattice is translated by a distance of one lattice period, a column of bubbles is annihilated on one end of the lattice while a column of bubbles is generated on the other end of the lattice.

In the column access design shown in Fig. 2, one layer of metallurgy is used for the lattice translation func-

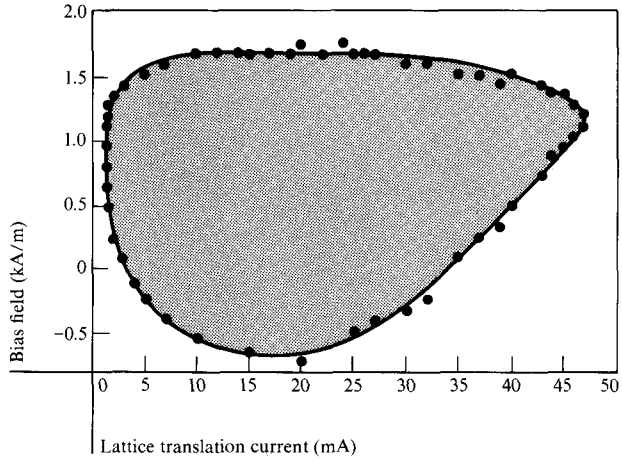

Figure 5 Operating margins for quasistatic (1 K column/s) lattice translation.

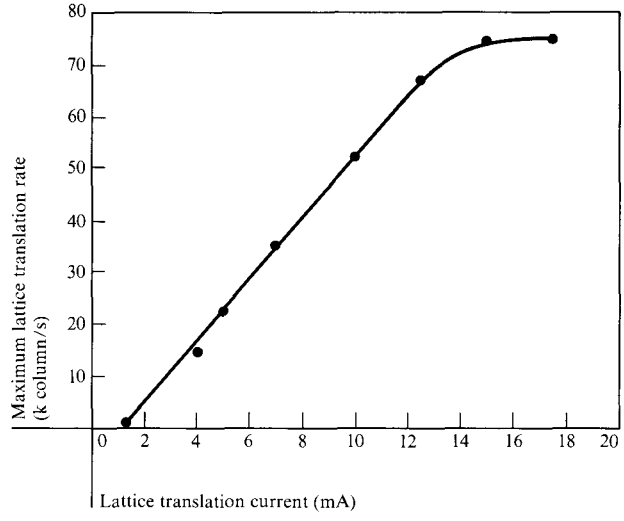

Figure 6 Relationship between maximum frequency of lattice translation and current in the lattice translation conductors.

tion and a second layer of metallurgy is used for the column translation function. The first layer of metallurgy may be placed directly on the garnet film; however, a spacer layer is generally used to minimize stresses in the garnet film. The second layer of metallurgy is then spaced from the surface of the bubble film by a distance equal to the sum of the initial spacer layer thickness plus the thickness of the insulator used between the two layers of metallurgy. The spacing between the conductor lines and the garnet film is a critical parameter. In general, the choice of whether to place the column translation conductors on the first or second level of metallurgy involves a consideration of power dissipation and access time and is dependent on the number of lattice translation conductor lines per access channel and the resistance of the lattice translation and column translation conductor lines.

In this design, we have chosen to place the column translation conductors on the first level of metallurgy and the lattice translation conductors on the second level of metallurgy.

The design of the conductors used for column translation is shown schematically in Fig. 4. This design utilizes the same bipolar four-phase arrangement of actuating current pulses used for lattice translation. The column translation conductors are widened, as shown, to reduce the force on the bubbles adjacent to the column of bubbles being translated. A pair of conductors is used to provide a channel for the column of bubbles during translation and to separate the column being translated from the remainder of the lattice. The dams have openings to allow the translation of the column of bubbles along the access channel. The dams play a major role in maintaining the bubbles adjacent to the column being translated in the hexagonal configuration. As a further aid to maintaining the lattice during translation, current is applied to the lattice translation conductors to hold the lattice. The combination of the restraining effects of the dams and the lattice translation conductors allows the column of bubbles to be translated without introducing defects in the lattice. As previously mentioned, the column translation conductors are on the first layer of metallurgy and are interconnected in series by crossovers using the second layer of metallurgy. The column of bubbles may be translated in and out of the storage lattice along channels which are defined by ion-milled dams outside of the storage lattice.

Device fabrication

The bubble material used was an LPE garnet film of nominal composition $Eu_{0.6}Y_{2.4}Fe_{3.9}Ga_{1.1}O_{12}$. The LPE film characteristics are as follows: a thickness, h, of 2.91 μm; saturation magnetization, M_s, of 13.5 kA/m; and a demagnetized stripe width, w_s, of 5.1 μm. The minimum field gradient needed to translate a bubble in this material is typically 0.08 kA/m per bubble diameter. The domain wall mobility is approximately 800 m^2/As.

The device fabrication process consisted in first selectively ion-milling the LPE film to create a topography on the surface of the LPE film. This topography provides isolation of bubbles within the lattice from the surrounding region as well as a guiding structure for the bubble lattice. The first and second metallization layers had a thickness of 0.5 μm and 1.0 μm, respectively. Schott glass deposited by electron-gun evaporation to the thickness of 0.5 μm was used as a spacer between the garnet

film and the first layer of metallization. Insulation between the two layers of metallization was achieved by a polymerized Shipley AZ 1350J resist 0.7 μm thick.

Test results

Quasistatic (1 K column/s) lattice translation operating margins are shown in Fig. 5. These data are taken for a 32-row by 34-column lattice having 32 stripe domains at each end of the lattice. The lattice initialization procedure involved applying an in-plane field to form parallel stripe domains and then pulsing the column generation conductors to form columns of bubbles. Details of the lattice initialization process have been previously described [11]. The operating margins shown in Fig. 5 were obtained by translating the lattice three column positions forward and three column positions backward, with the lattice situated so that the stripe-bubble interface does not move past a current-carrying conductor. During lattice translation, a bias modulating field was applied to minimize coercivity effects [13]. This bias modulating field was produced by applying a 2 MHz excitation to a 50 turn coil, 2 mm in diameter. The voltage waveform from the function generator used to drive the coil was a square wave; however, the inductance of the coil resulted in a current waveform and, hence, a bias field waveform, which was more nearly sinusoidal than square wave. The peak amplitude of the bias modulating field was 0.56 kA/m.

The quasistatic lattice translation operating margins shown in Fig. 5 demonstrate that the bubble lattice is a very stable domain configuration. At a drive current of 15 mA, the lattice can be translated with a bias field ranging from −0.64 to +1.7 kA/m. The failure mode at bias fields less than −0.64 kA/m was stripeout of a bubble, while the failure mode at bias fields greater than 1.7 kA/m was collapse of one of the stripe domains. Collins et al. [14] have shown that a confined array of parallel stripe domains is stable for bias fields up to 15 to 20 percent of M_s. This is consistent with the observation that stripe domains collapse with the sum of a peak bias modulating field of 0.56 kA/m plus a dc field greater than 1.68 kA/m. At currents less than 1.5 mA the lattice fails to move because the driving force is insufficient to overcome the effective coercivity.

Dynamic lattice translation characteristics were determined by increasing the lattice translation rate until failure occurred. Figure 6 illustrates the maximum frequency of lattice translation as a function of the current in the lattice translation conductors. These data indicate a linear relationship between the maximum rate of lattice translation and translation current for current levels up to 15 mA. The slope of the linear region in Fig. 6 is 5.8 K columns/s mA. If we assume a domain wall mobility of 800 m^2/As, Eggenberger's rigid lattice model [12] would imply a slope of about 60 K columns/s mA. A calculation by G. R. Henry [15], which includes the effects of lattice distortion and bubble size variation, correctly predicts the limiting velocity observed at currents above 15 mA and substantially reduces the difference between calculated and observed slopes.

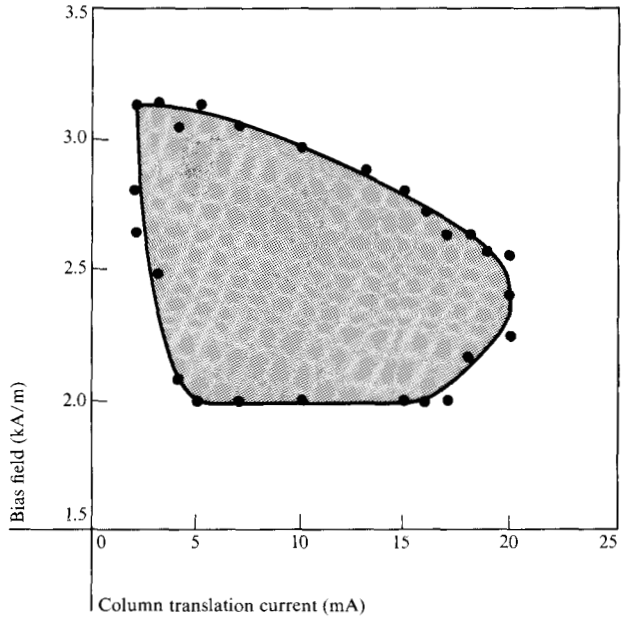

Figure 7 *Operating margins for quasistatic column translation.* Data are from a 12-bubble column having a stripe domain at each end of the column.

Quasistatic (five bubbles/s) column translation operating margins are shown in Fig. 7. These data were taken with a 12-bubble column having a stripe domain at each end of the column; the column was translated three bubble positions forward and three bubble positions backward. A 0.56 kA/m peak bias modulating field similar to that used for lattice translation was also used for column translation.

The dynamic column translation characteristics were determined by increasing the column translation rate until the column of bubbles failed to move a full three bubble positions forward and backward. The maximum rate of column translation is shown as a function of column translation current in Fig. 8. These data indicate a frequency response in the linear region of 23 K bubbles/s mA. This is about a factor of four greater than that observed for lattice translation. The 23 K bubble/s mA response is considered to be in reasonable agreement with the value predicted by the deformable lattice model [15] but is significantly less than the 60 K bubble/s mA value predicted by the rigid lattice model [12]. At current levels above five mA, the column translation rate levels off in a manner similar to that observed for lattice translation.

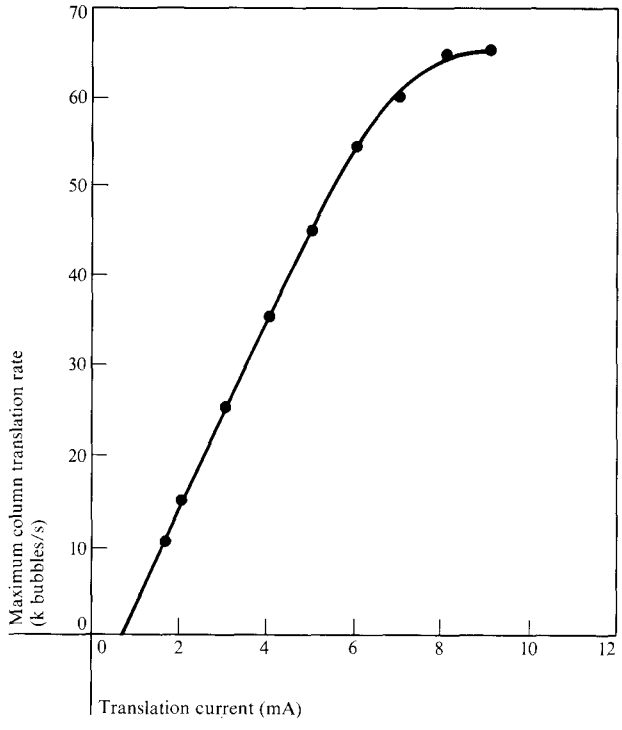

Figure 8 Maximum frequency of column translation as a function of column translation current.

Concluding remarks

The use of a lattice of closely spaced magnetic bubbles offers a technique for information storage with potential storage density roughly an order of magnitude greater than that of T-bar-like devices. A column-accessed configuration has been designed to permit rapid access of information stored in a bubble lattice. Design considerations indicate that such a configuration should have somewhere between four and sixteen access channels. Under these conditions the access rate is primarily dependent on the column translation rate, and the lattice translation rate is of secondary importance. This feature has the desirable consequence that lattice translation can be done at a relatively low rate and thereby minimize the on-chip power dissipation.

The two key functions required for a column-accessed bubble lattice device are the translation of the lattice so as to align the desired column with one of the input/output access channels and the translation of a column of bubbles along the access channel. Quasistatic lattice translation operating margins have been obtained which show that a lattice can be translated with a wide range of conditions of bias field and drive current. Quasistatic column translation operating margins are considerably smaller than those observed for lattice translation, although even the column translation margins are larger than are generally observed with devices designed to translate isolated bubbles. The lattice translation and column translation operating margins reported in this paper do not overlap in bias field. One solution to this problem is to raise the overall bias field during the column translation phase. A more attractive solution may be to modify the specific conductor design used to define the access channel.

Dynamic testing indicates that both the lattice translation rate and the column translation rate saturate at high drive current conditions. Henry's analysis shows that this saturation effect is due to the nonrigid aspect of the lattice. Fortunately, the coupling forces between bubbles in a lattice vary inversely with the square of the bubble diameter. Thus, the frequency saturation effects will be less of a problem with smaller bubbles. These considerations indicate that a design such as used in this paper, where there are four columns of bubbles per pair of conductor drive lines, is acceptable for lattice translation. The design is marginal, however, for column translation because the access rate is critically dependent on the column translation rate. A more satisfactory column translation design would be one in which a force is supplied directly to each bubble in the column.

Acknowledgments

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